A Standardised Pipeline for Patient-Specific Aortic Flow Modelling: Turbulent Flow Patterns in Transcatheter Aortic Valve Implantation Therapy

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Abstract

Aortic stenosis (AS) is the most common valvular heart disease in developed countries. Transcatheter Aortic Valve Implantation (TAVI) is the most common treatment for AS in patients at intermediate and high-risk for surgery. As its use expands to younger, lower-risk patients with longer life expectancies, TAVI's bioprosthetic durability holds increasing importance for its utility. Additional factors such as turbulent flow patterns in the aortic root, which may affect long-term hydrodynamic performance, device durability, and thrombus formation, are thus critical to consider alongside traditional measures of TAVI success.

We present a standardised Computational Fluid Dynamics (CFD) pipeline, based on clinical echocardiography and computed tomography (CT) data - including automated medical image processing, patient-specific model generation, flow simulation, and post-processing and analysis - to simulate turbulent aortic flow in individual AS patients undergoing TAVI. The pipeline is used to analyse flow patterns related to TAVI durability. We demonstrate its implementation for four retrospective clinical cases. Close collaboration with the clinical team ensures relevance, correct interpretation of clinical data, and clinical context which is crucial when analysing the results.

1. Introduction

Aortic stenosis (AS) is the most common valvular heart disease in developed countries, and has an average mortality rate of around 20% at 2 years and 50% at 5 years for severe AS if left untreated [1]. It is characterised by the incomplete opening of the aortic valve (AV), leading to reduced blood flow into the aorta. Transcatheter Aortic Valve Implantation (TAVI), a minimally invasive procedure in which a bioprosthetic replacement is implanted within the native AV to replace its function, has become a standard treatment for AS. Initially reserved for inoperable patients, TAVI is becoming more widely used in younger, lower-risk patient demographics with longer life expectancies. As its use expands to these groups, TAVI durability holds increasing importance. Thus, additional factors such as turbulent flow patterns in the aortic root, which may affect long-term hydrodynamic performance, device longevity, and thrombus formation, are critical to consider alongside traditional measures of TAVI success.

We therefore developed a standardised Computational Fluid Dynamics (CFD) pipeline based on clinical echocardiography and computed tomography (CT) imaging data - including automated medical image processing, patient-specific model generation, flow simulation, post-processing, and analysis - to simulate turbulent aortic flow in individual AS patients undergoing TAVI. The pipeline is used to analyse flow patterns related to TAVI durability, in close collaboration with the clinical team to ensure relevance, accurate interpretation of clinical data, and consideration of clinical context crucial for analysing the resultant flow patterns. We demonstrate the implementation of the pipeline in four retrospective clinical cases.

2. Methods

The pipeline uses CT and transthoracic echocardiography (TTE) imaging data, often available from standard clinical investigations of AS/TAVI, to generate patient-specific aortic models and simulate and analyse the resultant turbulent flow patterns (Figure 1).

A standardised domain of interest is obtained from medical image processing of the CT images and clipped to the

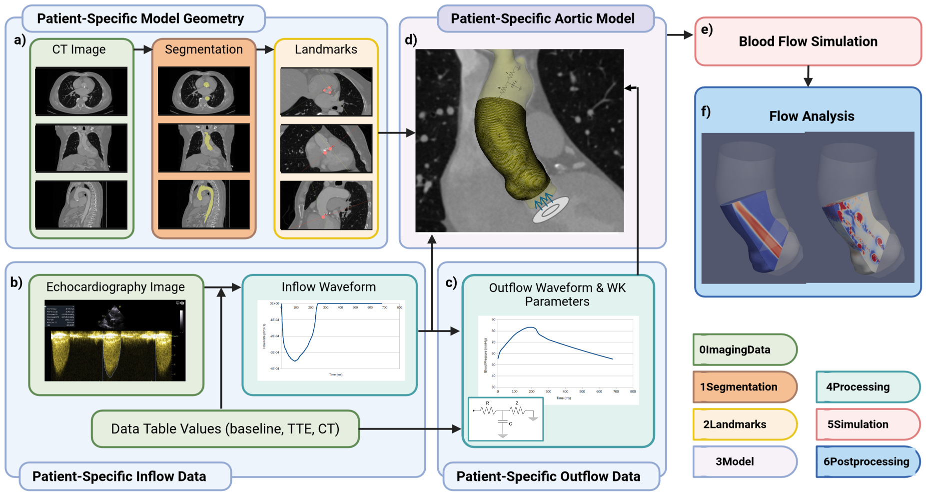

Figure 1. Model pipeline for patient-specific aortic flow simulation and analysis, including automated medical image processing, model generation (a-d), flow simulation (e), post-processing and analysis (f).

aortic root using anatomically-defined landmarks (Figure 1a,d). The AV is represented simply as a circular inflow with radius and flow rate determined from the patient's TTE data and velocity trace from the continuous wave (CW) Doppler images (Figure 1b). A three-element Windkessel model at the outflow boundary represents the downstream vasculature, with parameters determined from the derived inflow waveform and TTE data (Figure 1c). The patient-specific model and boundary conditions are used as input for a finite element-based CFD solver utilising a residual-based variational multiscale – large eddy simulation (RBVMS-LES) approach to solve for the expected transitory/turbulent flow and analyse the resultant flow patterns for TAVI durability (Figure 1e,f) [2].

2.1. Software Requirements

The pipeline is presented with the software we chose to complete each task, however, we note flexibility in this choice as long as care is taken to ensure compatibility.

Image Processing The open-source medical image processing software 3DSlicer (`https://www.slicer.org`) is used to view and convert anonymised DICOM (Digital Imaging and Communications in Medicine, standard format for medical images) images, to nearly raw raster data (nrrd, standard format for scientific visualisation/processing) for image processing. The open-source tool Engauge Digitizer (`https://sourceforge.net/projects/digitizer/`) is used to extract data points from traces in the TTE CW Doppler images (jpeg snapshots) into comma separated values (csv) files for the generation of patient-specific inflow boundary conditions. A deep learning (DL) approach based on the nnU-Net segmentation framework was developed to segment and reconstruct the aortic model from the CT images, implemented using the 3D low-resolution configuration of nnU-Net and fine-tuned using a misclassification loss function [3]. The open-source Seg.A dataset from the MICCAI 2023 challenge was used for training and validation, and all experiments were conducted on an NVIDIA A100 GPU with 40 GB of memory using the high-performance computing (HPC) cluster (Andrena) at QMUL [4].

Model Generation 3DSlicer is used to obtain necessary multiplanar reformatted views, place landmarks, edit segmentations, and generate model centrelines (SlicerVMTK: `https://github.com/vmtk/SlicerExtension-VMTK`). The open-source data visualisation software ParaView (`https://www.paraview.org/`) and custom python scripts are used to calculate additional landmarks and quantities for model generation. NumeriCor Studio (academic version: `https://numericor.at/rlb/wordpress/resources/`) is used to clip the model and produce the final geometry for meshing.

Processing Custom bash and python scripts are used to process CT and TTE measurements, digitised CW Doppler traces, landmarks, and geometries, with the open-source software meshtool (available with openCARP: `https://opencarp.org/`) to produce the final mesh and boundary condition data required for simulation [5, 6].

Simulation An in-house finite element-based fluids solver developed by the CARPentry team (FluidSolve, closed-source, `https://carpentry.medunigraz.at/`) and implemented on the ARCHER2 HPC (`https://www.archer2.ac.uk/`) is used to solve the problem defined by the patient-specific geometry and boundary conditions. A residual-based variational multiscale - large eddy simulation (RBVMS-LES) approach is used to model the expected transitional/turbulent flow [2].

Postprocessing Custom scripts utilising meshtool and igbutils utilities (open-source, included with openCARP) are used to perform calculations and extract and convert data from the igb format outputs of the simulation (CARPentry format) to alternative formats for visualisation. ParaView is used for visualisation and further postprocessing.

2.2. Workflow

0ImagingData The user begins with the raw anonymised CT images, TTE snapshots, and formatted data table with the necessary information for model generation and analysis of suitable cases. CT images are checked for suitability for modelling by both the modelling and clinical teams and converted in 3DSlicer ready for segmentation. A technician drawn trace in the TTE CW image is traced and digitised using Engauge Digitizer to produce a time dependent velocity curve of the flow at the AV for processing.

1Segmentation The anonymised nrrd CT images are uploaded to the HPC (Andrena) as input to the trained segmentation framework, which is run using an NVIDIA A100 GPU with 40 GB of memory to generate segmentation masks of the aorta.

2Landmarks Anatomical landmarks are placed within the CT image for standardised anatomical processing of the generated segmentation masks. The interactive plane reformatting tool in 3DSlicer is used to reproduce clinically validated multi-planar reformatting methods and obtain a double oblique view of the aortic annulus, with the lowest insertion points of the three native AV leaflet cusps visible in the same plane [7]. Landmarks are placed at each point using mark-up points (mrk.json) to define the annular plane. The centre of the three landmarks is used to define the annulus centre. These points are checked for accuracy by the clinical team and exported for processing.

3Model Necessary edits and extension of the segmentation mask into the left ventricular outflow tract (LVOT) are completed in 3DSlicer using the double oblique view of the aortic annulus, which can be reproduced using the annular landmarks. The final segmentation is checked for irregularities and good representation of the anatomy, and the surface exported in stereolithography (stl) format to produce the anatomical model of the aorta. The centreline is extracted using the SlicerVMTK extension, taking the annulus centre as the start point, and the centreline model (vtk) used to identify and place an additional landmark at the first branch point at the brachiocephalic artery.

The aorta model is opened in NumeriCor Studio and an 'autofix' step applied to correct any irregularities or issues in the surface mesh. Necessary manual corrections can be made at this stage. The surface is then clipped using a cylindrical tool at the annulus centre and identified first branch point, using the landmarks and calculated centreline directions at these locations. This can be performed by clipping the surface or by generating a volumetric mesh and clipping the volume. The contour or surface generated by the clipping is closed and/or remeshed, and the final meshed geometry exported in CARP format (pts, elem, lon) for further refinement and processing.

4Processing In this step the model and boundary conditions are prepared for simulation. The radius of the inflow jet is set to the AV area, calculated using the TTE flow values. The digitised CW trace is smoothed and rescaled to the reported TTE values to ensure an accurate reproduction of the CW image and minimize the addition of further variability through processing. The velocity is then converted to a volumetric flow rate. In the absence of a CW trace, a representative template trace, scaled to the reported TTE values, is used. Patient-specific Windkessel parameters are calculated using the TTE flow and blood pressure values, and specified in the parameter file for the solver.

Finally, the clipped aortic mesh is resampled to the desired refinement for simulation. Edge thresholding and maximum diameter mesh traversal (using the annulus centre and branch point landmarks as seed points) in meshtool are used to automatically extract the boundary surfaces for implementation of the boundary conditions. All files are formatted and given in the specified units as required for the solver, and copied to the simulation folder.

5Simulation The parameter and submission files for the solver and HPC (ARCHER2) are updated with the necessary information, such as paths to the mesh and boundary condition data, calculated patient-specific parameters, time period to be simulated, and other required information such as solver type, time step, solver tolerances, and fluid properties. The scripts are uploaded to the HPC with the mesh and boundary condition files and the job submitted for simulation. Any postprocessing calculations performed by the solver are submitted as a postprocessing experiment following the completion of the initial simulation.

6Postprocessing Initial postprocessing is completed on the HPC (ARCHER2) using igbops to allow for manageable processing of the large simulation output files. Final outputs are converted to a more manageable file format compatible with postprocessing software (e.g. Ensight Gold, `https://www.ansys.com/en-gb/products/fluids/ansys-ensight`) using meshtool, and downloaded for further processing. The results are visualised and analysed in ParaView, using the patient-specific landmarks and centrelines to define specific regions of interest for flow quantification and analysis.

3. Results & Conclusions

Successful implementation of the pipeline was demonstrated in an initial study of four retrospective clinical cases with severe AS (Figure 2). Standardised models were gen-

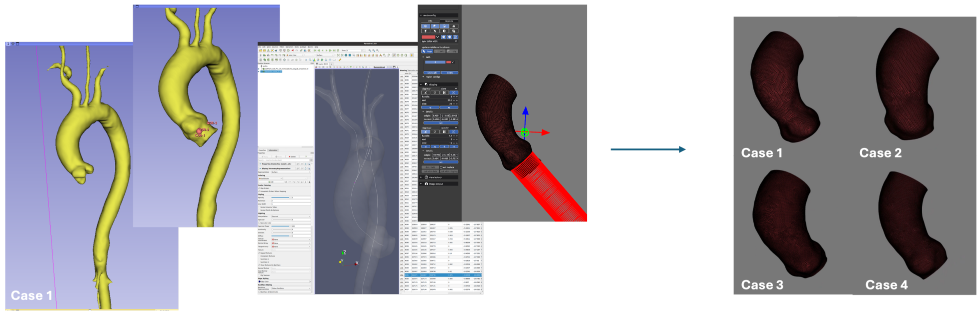

Figure 2. Implementation of the model pipeline to generate standardised aortic root models for four clinical cases.

erated across cases from the patients' CT and TTE imaging data and the resultant aortic flow simulated to investigate flow patterns related to TAVI durability [8]. By further automating and expanding to additional clinical cases, we aim to provide a tool for clinicians to predict TAVI longevity, allowing tailored therapy for individual patients.

Although existing tools, such as Simvascular (`https://simvascular.github.io/`), allow model generation and flow simulation from medical images, standardised methods are needed to reproducibly construct models across patient cohorts. Our standardised methodology, utilising clearly and clinically defined anatomical landmarks and patient-specific boundary condition data, ensures reproducible model generation and minimisation of additional errors introduced during processing, and allows us to make direct comparisons between cases. The further use of DL and automated scripting allows model generation on more realistic timelines for clinical applications.

Although the current iteration of the pipeline represents the AV simplistically as a circular inflow jet, it allows us to obtain useful haemodynamic information regarding aortic flow and TAVI durability. The use of echocardiography measurements, which can vary significantly between operators, can also add uncertainty into the models. Future work includes the more direct inclusion of the AV and investigation of the impact of TTE-derived boundary conditions on simulated flow, as well as further automation and application to wider clinical datasets. As we move towards the integration of modelling and digital twins in healthcare, continued collaboration with the clinical team is essential to understand such limitations, ensure appropriate integration of clinical data in models, and interpret results in the correct clinical context for each individual patient [9].

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